Linear and Nonlinear Verification of Gyrokinetic Microstability Codes

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Background

- Most gyrokinetic microstability codes now include passing and trapped electrons, accurate plasma shaping, multiple kinetic species, collisions, magnetic fluctuations, finite ρ^*, and equilibrium $\mathbf{E}\times\mathbf{B}$ flow shear.
- Linear predictions of mode frequencies are now routine for interpreting turbulence and/or transport measurements in experiments.
- Nonlinear predictions of transport and/or turbulence characteristics in experiments are becoming more commonplace.
- **However, the codes have not been verified (shown to correctly solve the underlying equations) for present-day experiments spanning a range of discharge conditions.**
- No analytical verification in such regimes $\Rightarrow$
  - "**benchmarking**": Code is "correct" if it agrees with others (unlikely all would produce exact same erroneous result).

Background (cont.)

- An “analyst” develops experimentally relevant benchmarks through apples-to-apples comparisons between codes.*
- “Apples-to-apples”?
  - same plasma
  - same plasma shaping [EFIT or Miller formalism [R. L. Miller, et al., Phys. Plasmas **5** (1998) 973)]
  - same physics (EM, collisions, trapped electrons, etc.)
  - both periodic or global radial domain
  - both include $\mathbf{E}\times\mathbf{B}$ shear?
  - sufficient temporal, spatial, velocity-space resolutions

* GYRO and GS2 in what follows. Grant renewal calls for adding particle-in-cell (PIC) code GEM.

Validation NOT Shortcut to Verification

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- Codes rarely agree with limited set of experimental data using default plasma profiles.
- Plasma profiles must be independently adjusted in all combinations within experimental uncertainties to seek agreement.
  - **No way to distinguish code errors from experimental uncertainties**
- Codes have never been shown to agree with all experi-mental data:
  - Electron, ion, impurity fluxes:
    - Energy, particle, momentum
  - Fluctuation parameters, e.g.,
    - electron density, temperature fluctuation levels
    - density/temperature phase angle
    - mean poloidal wave number

Benchmarking Algorithm

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1. Extract data from transport analysis code, e.g., TRANSP or ONETWO.
2. Generate linear GYRO input file; translate to a GS2* input file.
3. Run both codes including “full physics.”
4. If differences found between codes, remove shaping, collisions, etc. individually until agreement is reached ⇒ “reduced” benchmark.
5. Reinstate physics one at a time in different order.
   - agreement ⇒ successively more complex benchmarks
   - disagreement ⇒ source(s) of problem, e.g., collisions or combination of elongation and trapped electrons
6. Present results to code developers who must first concur with findings, then help seek resolution.
7. Repeat steps 5 and 6 until all terms included ⇒ “full physics” benchmark.
8. Generate nonlinear GYRO, GS2 input files. Repeat steps 3-7.
9. Repeat entire procedure for different radius, discharge, time, machine.

* and GEM in future?

GYRO/GS2 Comparisons

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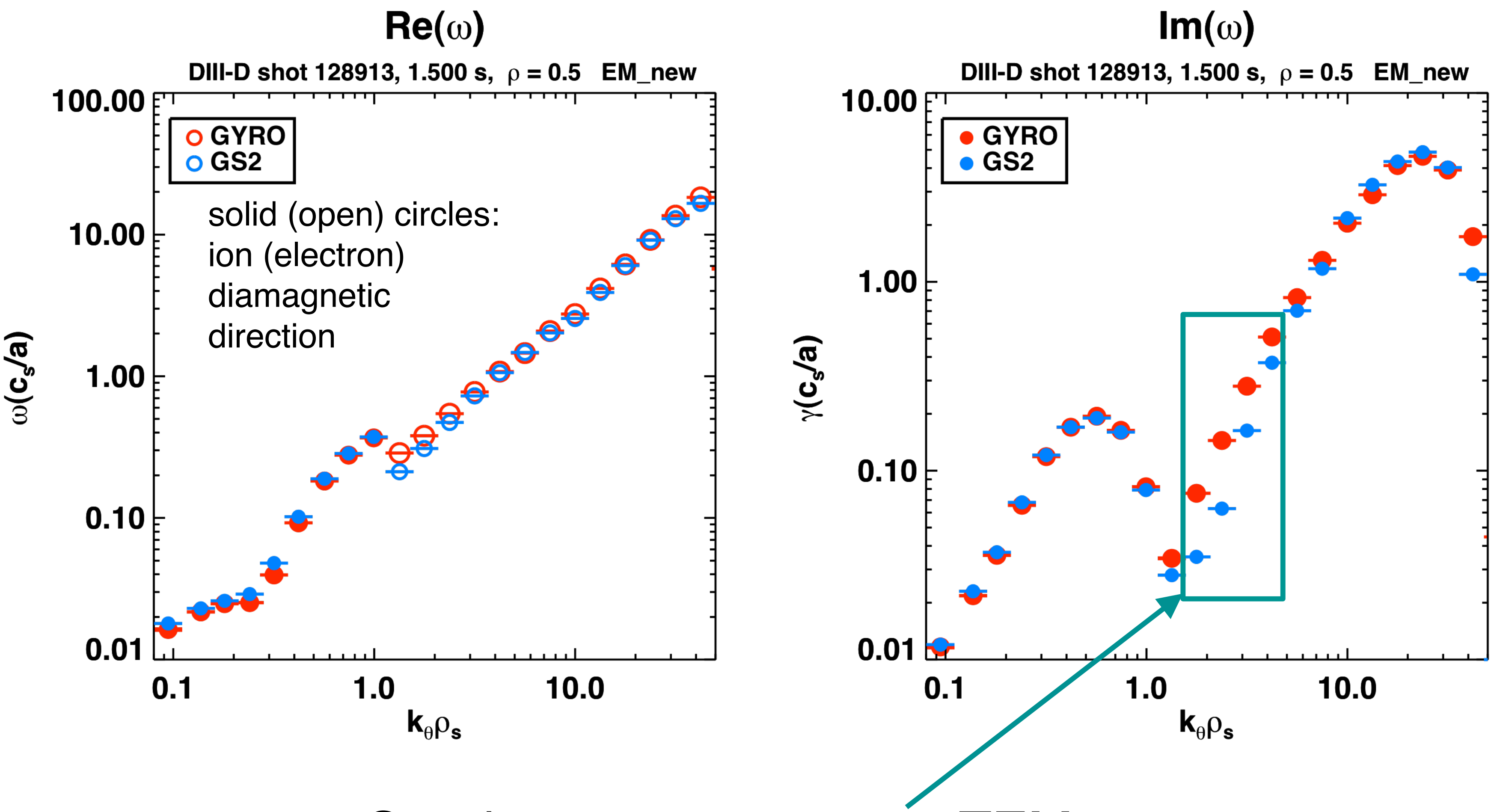
n_e (10^{19} m^{-3})	2.11
T_e (keV)	0.992
n_i/n_e	0.935
n_{imp}/n_e	0.011
$T_i/T_e = T_{inp}/T_e$	0.828
$a/L_{ne} = a\,\mathrm{dln}(n_e)/\mathrm{d}r$	1.07
$a/L_{ni} = a\,\mathrm{dln}(n_i)/\mathrm{d}r$	1.07
$a/L_{Te} = a\,\mathrm{dln}(T_e)/\mathrm{d}r$	2.64
$a/L_{Ti} = a\,\mathrm{dln}(T_i)/\mathrm{d}r$	1.81
$a/L_{Timp} = a\,\mathrm{dln}(T_{imp})/\mathrm{d}r$	1.81
$R_0(r)/a$	2.81
$\Delta = \mathrm{d}R_0(r)/\mathrm{d}r$	-0.0855
q	1.805
$\mathrm{s} = \mathrm{r}\,\mathrm{dln(q)/dr}$	0.580
κ	1.30
$s_\kappa = r\,\mathrm{dln}(\kappa)/\mathrm{d}r$	0.0457
δ	0.150
$s_\delta = r\,\mathrm{d}\delta/\mathrm{d}r$	0.174
β	0.00346
ρ^*	0.00366
Z_{eff}	1.32
$\nu_{ei}\,a/c_s$	0.112

- DIII-D shot 128913, $\rho = 0.5$, $t = 1.5$ s (1 NB source)
  - C. Holland, A. E. White, et al., Phys. Plasmas **16**, 052301 (2009)
- Included:
  - electromagnetic ($\delta B_{||}$ neglected)
  - passing and trapped electrons
  - Miller shaping
  - electron collisions (Lorentz model)
  - one impurity (C^{+6})
- Neglected:
  - Finite ρ^* ($\rho^* \ll 1$ anyway)
  - $\mathbf{E}\times\mathbf{B}$ flow shear

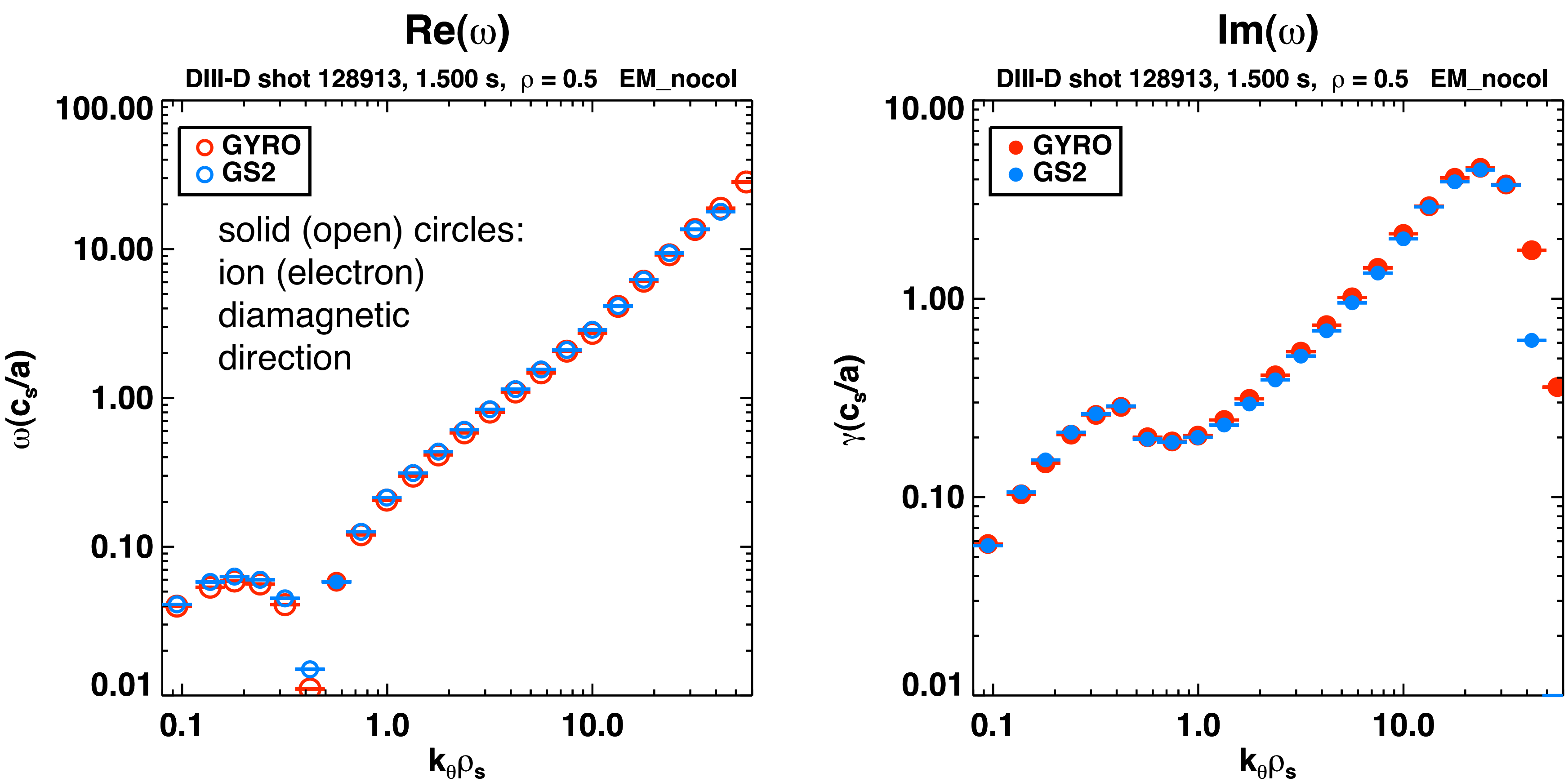
Frequencies for "Full Physics"



- Good agreement except TEM range

Since TEM's are sensitive to collisions, next remove

Frequencies without Collisions



- Excellent agreement

⇒ **Differences in collision operators**

Nonlinear Simulations

- 16 poloidal modes
- $0 < k_\theta \rho_s \lesssim 1$
- $L_\theta \sim 100\rho_s$ (wavelength of lowest nonzero k_θ)
- $L_r \sim 150\rho_s$
  - $n_r = 144$ (GS2) $\Rightarrow \Delta r \sim \rho_s$
  - $n_r = 192$ (GYRO) $\Rightarrow \Delta r \sim 0.8\rho_s$
- Velocity-space grid points:
  128 (GYRO), 592 (GS2)
- Fluxes from $\mathbf{B}_\perp$ found to be negligible

Nonlinear

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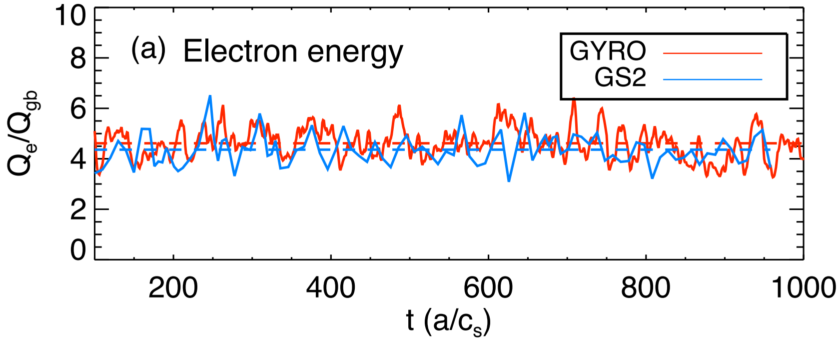
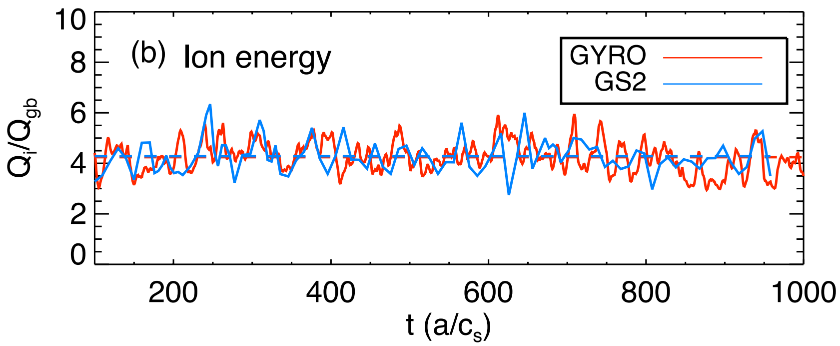
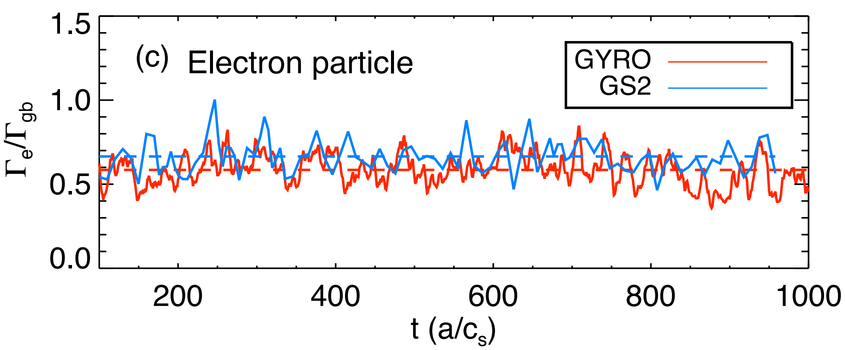
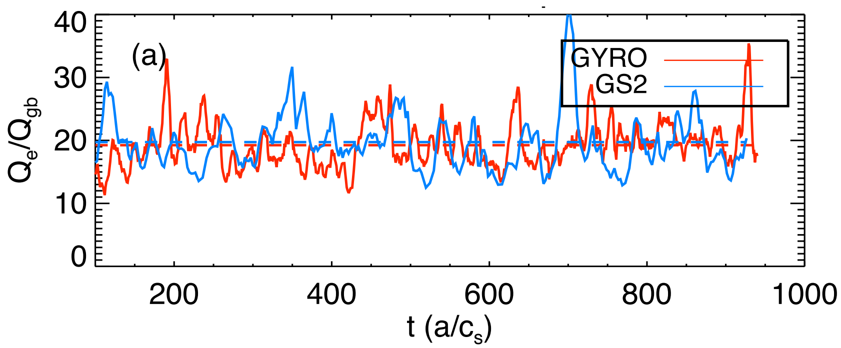
with **collisions**

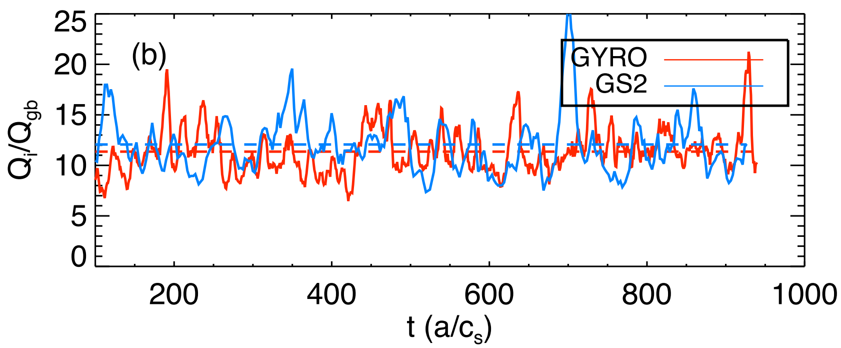


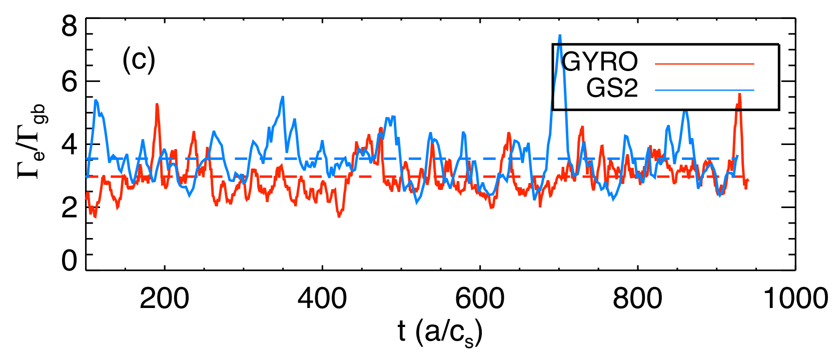




omitting collisions

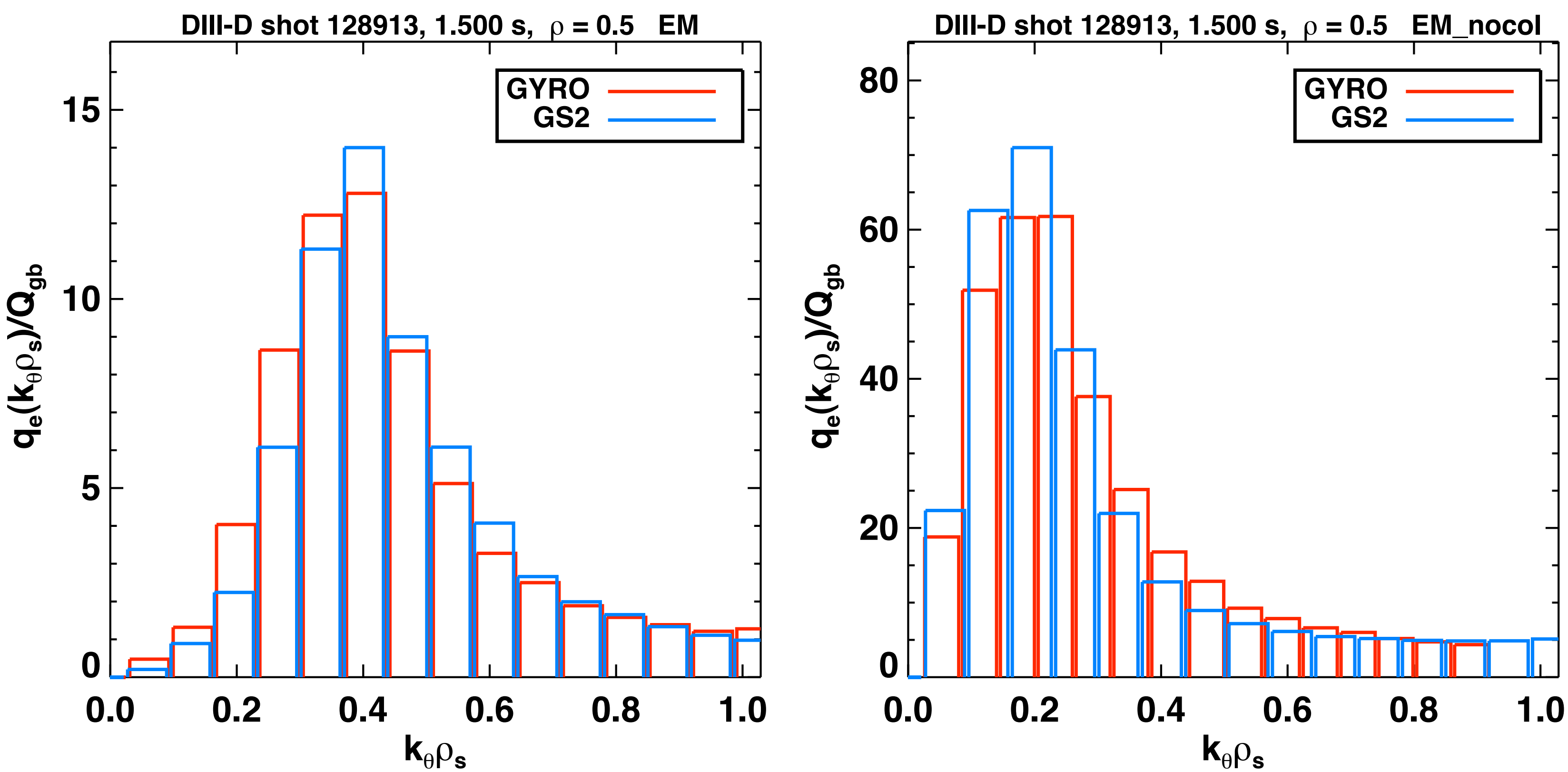






Electron Energy Flux Spectra

with **collisions** | **omitting collisions**



- Good agreement
- Spectra with collisions peak at ~ half that with collisions

Conclusions

- For the plasma considered here, GYRO and GS2 frequencies and fluxes agree well for model including
  - magnetic fluctuations (transport from $\delta\mathbf{B}$ small, however)
  - passing and trapped electrons
  - Miller shaping
  - electron collisions (Lorentz model)
  - one impurity (C^{+6})

- Benchmarks at mid-radius with “full physics” (except $\rho^* \Rightarrow 0$, no $\mathbf{E}\times\mathbf{B}$ flow shear) have been formulated.

Future Work

- Resolve linear discrepancy in TEM region with collisions.
- Repeat at radius farther toward edge.
- Include $\mathbf{E}\times\mathbf{B}$ flow shear; compare to results of C. Holland, A. E. White, et al., Phys. Plasmas **16**, 052301 (2009).
- Investigate other discharges:
  - DIII-D high-β, strong shaping, suggestions?
  - C-Mod EDA H-mode, suggestions?

- If changes are made to one or both codes, code comparisons will be repeated. (Validation results by other groups will have to be revisited.)

- Incorporate GEM or GENE into benchmarking/verification.
  - Would greatly enhance credibility (GEM ⇒ PIC vs continuum)